AD-A105 499 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH F/G 4/2
APPLICATION OF AN INTERACTIVE ONE-DIMENSIONAL CLOUD MODEL TO WA--ETC(U)
MAR 79 T D CRUM
UNCLASSIFIED AFIT-CI-79-292T-S NL

1 OF 1
AD A
105499

END
DATE
FILMED
11-81
DTIC

The Pennsylvania State University

The Graduate School

Department of Meteorology

Application of an Interactive One-Dimensional Cloud Model to Warm Season Afternoon Convection

A Thesis in

Meteorology

by

Timothy Doyal Crum

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

Mar[redacted]79

UNCLASS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 79-292T-S	2. GOVT ACCESSION NO. AD-A105499	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Application of an Interactive One-Dimensional Cloud Model to Warm Season Afternoon Convection		5. TYPE OF REPORT & PERIOD COVERED THESIS/~~DISSERTATI~~ON
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Timothy Doyal Crum		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFIT STUDENT AT: Pennsylvania State Univ		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS AFIT/NR WPAFB OH 45433		12. REPORT DATE Mar 1979
		13. NUMBER OF PAGES 63
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASS
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

30 SEP 1981

Fredric C. Lynch

18. SUPPLEMENTARY NOTES

APPROVED FOR PUBLIC RELEASE: IAW AFR 190-17

FREDRIC C. LYNCH, Major, USAF
Director of Public Affairs
Air Force Institute of Technology (ATC)
Wright-Patterson AFB, OH 45433

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

ATTACHED

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

The signatories below indicate that they have read and approved the thesis of Timothy Doyal Crum.

Date of Signature:	Signatories:
12 January 1979	John J. Cahir John J. Cahir, Associate Professor of Meteorology, Thesis Advisor
12 Jan 1979	Alfred K. Blackadar Alfred K. Blackadar, Head of the Department of Meteorology
13 January 1979	Richard A. Anthes Richard A. Anthes, Professor of Meteorology, Graduate Faculty Reader

ABSTRACT

A one-dimensional cloud model was used interactively to predict convective cloud tops. The model forecasts were verified against tops determined from enhanced infrared satellite images and radar reports.

The cloud model was run on a minicomputer using observed environmental soundings and allowing sounding modification by the forecaster. The main concern of the experimentation was spring and summer afternoon convective activity.

Results showed that the cloud model correctly forecast the occurrence or nonoccurrence of convection in 78 of 99 cases studied. In frontal situations, interaction with soundings appeared to improve cloud top forecasts; interaction appeared to be most critical for the boundary layer. Interactive forecasts of tops of prevailing convection had a root-mean-square error of 2.0 km and were within 1.5 km of the observed tops in 69% of the cases studied; those for the more isolated highest convective tops had a root-mean-square error of 1.6 km and were within 1.5 km of the observed tops in 70% of the cases.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. John Cahir for his suggestions, encouragement, and critical review without which this thesis would not have been accomplished.

Appreciation is also extended to Dr. Richard Anthes for his suggestions and allowing the use of his cloud model.

The author's attendance at the Graduate School of The Pennsylvania State University was made possible by the Air Force Institute of Technology.

This research was funded in part by the Systems Development Office, National Weather Service under contract T-35406.

1.0 INTRODUCTION

1.1 Review of the problem

Forecasting the height of convective cloud tops has been and is being done in support of military and commercial aviation. Most recently, Darrah (1978) and Bonner and Kemper (1971) have discussed the positive correlation between convective cloud top heights and storm severity.

Despite the fact that weather centrals and forecasters on the local level are expending time and resources to make cloud top forecasts, little beyond subjective judgement, the slice method, or the parcel method is operationally available as guidance in making convective cloud top forecasts.

The immediate future offers minicomputer capabilities with the National Weather Service's Automation of Field Operations and Services (AFOS), the Air Force Air Weather Service's Automated Weather Distribution System (AWDS), and the Naval Weather Service's Naval Environmental Display System (NEDS). This real-time minicomputer capability could allow the forecaster to replace subjective cloud top forecasts with an objective cloud model.

1.2 Review of convection forecasting

The slice method and parcel method are two general pseudo-adiabatic thermodynamic convection models. These models have been used as predictors of the maximum height to be reached by convective cloud tops. The main assumption of the parcel method is that a rising parcel of air moves adiabatically in an undisturbed environment without mixing with the environment. It is the assumption of the parcel not

mixing with its environment that is the greatest weakness of the parcel method and the reason why the use of the parcel method tends to overforecast convective heights. J. Bjerknes (1938) introduced the slice method, in which the compensatory sinking and resultant adiabatic warming taking place outside of convective clouds is taken into account. The warming of the environmental air reduces the temperature excess of the rising parcels and hence their buoyancy. However, the slice method, which tends to underforecast convective heights (Myers, 1966), requires knowledge of the relative areas of upward and downward vertical motion, which is difficult to forecast.

Austin (1948) cited Vonnegut, Cunningham, and Katz (1946) and Stommel (1947) as being among the first to note that observations showed that the air in convective clouds is usually colder than either the parcel method or the slice method predict. They attributed this phenomenon to entrainment of environmental air into the cloud. Entrainment was described by Byers and Braham (1949) as the process whereby a moving stream pulls in, because of pressure forces, or captures and drags along because of viscous forces, part of the environment.

To study convective processes in a more complete way than the pseudo-adiabatic thermodynamic models allow, numerous cloud models of various types have been developed. Houghton and Cramer (1951) constructed an analytic model of the interaction of buoyancy, vertical motions, and entrainment in a cloud, the first of many such models. The complexity and scope of cloud models are dependent upon how the cloud physics, geometry of the cloud, entrainment, and cloud-environment interactions are handled and also on how many dimensions and physical processes are considered.

Many cloud models were developed for a specific purpose, such as testing theories on cumulus cloud seeding, parameterizing the effects of cumulus on larger-scale models, or testing different ways to represent physical processes in clouds. Weinstein and Davis (1967), Simpson et al. (1967), and Simpson and Wiggert (1969) all employed cloud models that predicted cloud tops for both seeded and unseeded cumulus towers. They were able to obtain predicted cloud tops that had mean errors of less than 1 km and high correlation coefficients with the observed tops. These experiments were supported by aircraft measurements of atmospheric parameters and the radius and height of the convective cells being studied. Also, supplementary rawinsondes and/or dropsondes in addition to 0000 and 1200 Greenwich Mean Time (GMT) rawinsondes were available. These supplementary observations allowed accurate initialization and verification of the models. Simpson et al. (1967) remarked that their prediction errors increased with decreased sounding availability.

Matthews and Henz (1975) compared the Kreitzberg and Perkey (1976) MESOCU cloud model's results with observed cloud development. The model simulates cumulus interaction with the environment, synoptic or mesoscale lifting, convective cloud development, subsidence, mixing of the cloud into the environment, entrainment of environmental air into the cloud, low-level eddy mixing, solar heating, and subcloud evaporation. The MESOCU model was used to predict cloud development on five days in Colorado where supplementary radar and upper air data were available. Cumulus clouds which formed near or after rawinsonde launch time in a downstream location were used for verification. The model showed skill in forecasting the observed tops. Model-predicted and radar-estimated cloud tops had a standard deviation of 1.15 km.

Sanders and Garrett (1975) used a cloud model with 1200 GMT summer soundings in the Tampa, FL, area as model input. They related the computed height of the model's 2 km radius plume to the occurrence or nonoccurrence of audible thunder at Tampa. The model exhibited modest predictive skill when compared to the predictive capabilities of the Showalter Index and the precipitable water depth from the surface to 50 kPa. Sanders and Garrett did not attempt to use the model on predicted soundings, although they recognized that possibility.

Kuo (1974) and Anthes (1977) have discussed how the release of latent heat by cumulus towers drives large-scale tropical disturbances and the need to include these effects in hurricane models. However, since the horizontal scale of cumulus clouds is much smaller than the grid scale representing the large-scale hurricane flow, the influence of convection must be parameterized in the larger model. It was out of this need to parameterize the effects of cumulus convection on the large scale that the Kuo (1965, 1974), Kreitzberg and Perkey (1976), Anthes (1977), and other cloud models were developed. The Anthes model was chosen as the basis of this research.

1.3 Statement of the problem/research objectives

This thesis is a preliminary test of the hypothesis that forecasters using a relatively simple cloud model can exhibit convective cloud top forecasting skill in an operational, interactive mode.

The Anthes' (1977) one-dimensional cloud model, coded for the Pennsylvania State University Department of Meteorology's Digital Equipment PDP-11/34 minicomputer, was tested on 99, April through August, 1978, daytime cases. The test was restricted to investigating

how well the model predicts the occurrence or nonoccurrence of daytime convection and for the affirmative case, how well it forecasts tops compared with observed tops estimated from radar and satellite data. Frontal and nonfrontal cases are discussed together and separately.

One of the features of the minicomputer is the ability to easily perform interactions, such as manipulating the input data for a model. This interactive capability, simulating real-time forecaster input, was tested by modifying the environmental soundings in a manner that was consistent with subjectively estimated synoptic-scale boundary layer and upper level changes. Each modification was made for four different cloud radii to determine which of several methods of handling boundary layer moisture and other modification procedures produces the most useful results for predicting prevailing tops and also tops of large cells, such as supercells.

1.4 Scope of the research

This study was limited to warm season situations; all experiments are over United States land areas east of 100° W longitude. The input data was 1200 GMT rawinsonde data at significant levels. As the soundings were interpolated linearly to 5 kPa increments for use by the cloud model and because there are rapid spatial and temporal changes of the lower atmosphere, it is certain that there were errors in details, especially those related to the numerous small inversions found in soundings. However, interaction may make it possible to introduce the basic controlling factors for convection such that convection occurrence and height determination can be reasonably estimated. For this developmental work, hourly surface reports, surface and upper

air analyses, and National Weather Service (NWS) forecasts were used for supplemental data and rationale for interaction decisions. In a real-time forecasting environment, these data must be forecast.

Cloud top height and occurrence or nonoccurrence of convection was determined by NWS radar reports, some supplementary military radar reports, and enhanced infrared (IR) satellite imagery distributed by the National Environmental Satellite Service. These data sources were limiting owing to the short lifetime and rapid fluctuations of convective cells and because the tops are reported at most twice hourly. Satellite imagery was used to better determine the representativeness of radar-reported maximum tops. Case studies were performed only for sites which had the above mentioned data available.

In Chapter 2, the minicomputer concept in the future of weather forecasting and an outline of the Anthes cloud model is discussed. In Chapter 3, the framework of the experiments that were run and the verification method is given. Chapter 4 contains the presentation and discussion of the model results. Presented in Chapter 5 is a summary of the experiments and concluding remarks on what the cloud model experiments show and suggestions on the direction that future research of this type might take.

2.0 DESCRIPTION OF THE MINICOMPUTER SYSTEM AND THE CLOUD MODEL

2.1 Interactive computer concept

The NWS is installing the AFOS system in its forecast offices and plans to have most of the equipment in place by 1981 (Klein, 1978). In the 1980's the Navy will be installing its NEDS and the Air Force its AWDS.

When the AFOS system is installed, teletypewriter and facsimile machines will be replaced with cathode ray tube displays and minicomputer systems. Hard copies of graphic and alphanumeric data can be made by peripheral devices. Use of the AFOS system will allow more rapid transmission of data, automate routine forecaster tasks, and allow the forecaster to have more objective analyses of data available for use than at present. The storage and computational capabilities of the general purpose minicomputer, which is the heart of the system, could allow the forecaster to objectively analyze data and to run relatively small forecast programs, such as a cloud model.

The Meteorology Department of the Pennsylvania State University operates a Digital Equipment Corporation PDP-11/34 computer. This computer has a 64K-word (K=1024) core and three 2.5 megabyte disc drives, one Tektronix Model 4012 storage-type graphics terminal and a few peripheral devices, such as a tape drive, line printer, and keyboard terminals. The capabilities of this system are similar to, but less than those of AFOS, NEDS, or AWDS in most respects. Weather observations are supplied to the PDP-11/34 via the Federal Avaiation Administration's medium-speed 604 circuit.

The cloud model, along with other analyses and forecast programs, is readily accessible from the discs to the operator of the PDP-11/34 for use on real-time or stored data (Cahir et al., 1976; Cahir et al., 1978).

2.2 The model

The cloud model, described by Anthes (1977), follows a parcel of air, the top portion of the cloud, that is 1 km thick and has a variable radius of 1, 2, 4, or 8 km. The motion of this parcel is governed by

$$\frac{dw}{dt} = \frac{g\left(\frac{T_c - T_e}{T_e}\right)}{1 + \gamma} - \frac{gQ}{1 + \gamma} - \mu w^2 \qquad (1)$$

where w is the vertical velocity, g is gravity, T_c is the cloud temperature, T_e is the environmental temperature, γ is the "virtual mass coefficient" (set to 0.5) which takes into account nonhydrostatic effects, Q is the liquid water content of the parcel, and μ is the rate of entrainment of environmental air.

The entrainment rate used in (1) is

$$\mu = \frac{0.183}{R} \qquad (2)$$

where R is the radius of the parcel in meters. Hence, the entrainment has a decreasing effect with increasing radius.

The cloud temperature in (1) is determined by evaluating

$$T_c = \frac{T_c' + [\exp(\mu \cdot \Delta z - 1)]T_e}{\exp(\mu \cdot \Delta z)} \qquad (3)$$

where T_c' is the cloud temperature before mixing with the environmental air and Δz is the change of height between the computational level being considered and the previous computational level. The effect of entrainment on the cloud temperature and the decreased effect of entrainment with increased cloud radius can be seen in Fig. 1, which is an example of how the cloud temperature and cloud top of a modeled cloud vary for radii of 1 and 4 km.

The retarding effects on the parcel's acceleration due to liquid water being dragged along by the parcel are considered in the model. Since

$$\frac{dw}{dt} = \frac{dw}{dz} \cdot \frac{dz}{dt} = w\frac{dw}{dz} = \frac{d(\frac{w^2}{2})}{dz} \quad , \qquad (4)$$

the left-hand side of (1) can be interpreted as the change with height of the parcel's kinetic energy. The right-hand side of (1) can be seen to consist of three terms which are, respectively, the acceleration associated with entrainment-reduced buoyancy, the retardant force of liquid-water drag, and the deceleration associated with the entrainment of the air having no vertical kinetic energy. Thus, entrainment decelerates the parcel by both reducing its buoyancy and its kinetic energy.

Computation of the cloud base is accomplished by a process that uses the 100 kPa level as the surface and finds the lifting condensation

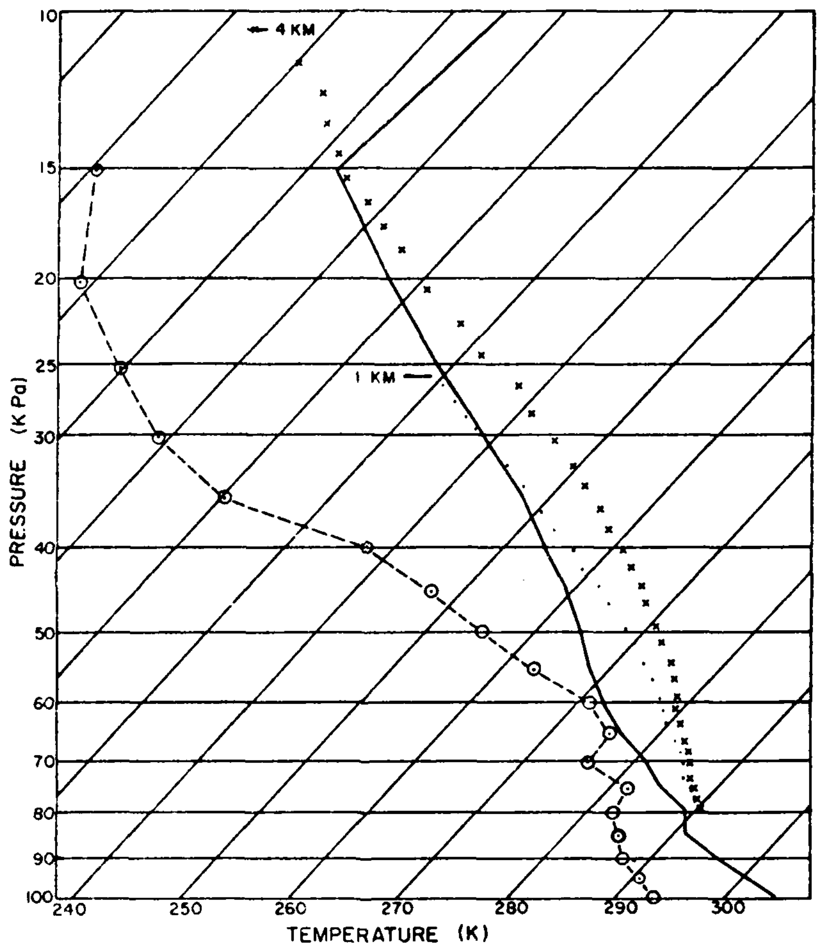

Figure 1. Trial sounding (solid and dashed) used by the cloud model and the resultant temperature profile for the 1 km (dotted) and 4 km (crosses) cloud.

level (LCL). For all LCL computations, the 100 kPa mixing ratio is used. If an LCL is found that does not have a temperature that is two-tenths of a Celsius degree greater than that of the environment, the 100 kPa temperature is increased one degree and the sequence of computations is performed again. This sequence is continued until a LCL that has a temperature that is at least two-tenths of a degree greater than the temperature of the environment is found. Thus, for all case studies, the model was forced to find a convective temperature and a cloud was formed by the model. The computed convective temperature was the minimum 100 kPa temperature required for the model to produce a cloud. The convective temperature used in the study for convection verification was corrected for sites with surface pressures not being at 100 kPa by using Poisson's equation

$$T_p = T_{100}\left(\frac{P_{sfc}}{100}\right)^{0.287} \tag{5}$$

where T_p is the corrected surface convective temperature, T_{100} is the computed 100 kPa convective temperature, and P_{sfc} is the actual surface pressure reported by the rawinsonde.

At the cloud base, the parcel is given an initial vertical velocity of 1 m s^{-1}. The model calculations are carried out every 1.0 kPa until the vertical velocity decreases to zero. The point where the vertical velocity reaches zero is defined as the cloud top.

2.3 Model input

Input to the cloud model consists of soundings for which temperature and mixing ratio values are linearly interpolated at 5 kPa

intervals from 100 kPa to 5 kPa. The temperatures and/or mixing ratios at any or all of these 5 kPa interval pressure levels can be changed by interaction, if desired.

In cases where the surface pressure is less than 100 kPa, the surface temperature is used at all of the 5 kPa interval pressure levels between the actual surface pressure and 100 kPa. The mixing ratio is handled such that the relative humidity of the air between the surface and 100 kPa is kept at the surface value. Where the surface pressure is greater than 100 kPa, the temperature and mixing ratio values of the pressure levels greater than 100 kPa are used along with those less than 100 kPa to find interpolated values for 100 kPa.

The 10 kPa temperature is used at 5 kPa. At levels where the dewpoint is not reported, above about 35 kPa, the mixing ratio is set to correspond to a relative humidity of 20%. Varying the relative humidity in these "bogus" data areas to as much as 120% resulted in no difference in the computed cloud top. This is in agreement with the result of Malkus, cited by Simpson et al. (1967), that showed that above 50-40 kPa, tropical clouds are insensitive to entrainment due to the small differences between saturated and environmental mixing ratios.

2.4 Model output

Outputs from the model include: the original sounding; the sounding actually used by the model after modifications were made; vertical velocity, cloud temperature, buoyancy acceleration, liquid water drag, and the parcel's liquid water content at each computational

level; temperature, pressure, and height of the computed cloud base; and the corrected surface temperature for which convection began.

The cloud radius values of 1, 2, 4, and 8 km are arbitrary, but are meant to represent the common range of cloud radii observed in the atmosphere.

2.5 Model limitations

An important consideration in using the one-dimensional cloud model for minicomputer applications is its small size and fast execution. The model results are immediately available on a line printer and are displayed on a graphics terminal. In such a small model, most cloud processes must be simplified greatly. It is the parameterization or neglect of some cloud processes that allows the model to be so compact.

It must also be stressed, that this use of the cloud model was for synoptic-scale forecasting of convection and maximum convective cloud tops. The model was not used to model individual cells or the sequential development of clouds through a summer day.

To incorporate some of the larger-scale effects that the model does not consider is the role of the forecaster in the interactive mode.

3.0 EXPERIMENTAL PROCEDURE

3.1 Case study selection

Selection of locations for case studies was dependent upon whether all of the necessary initial and verification data were available. For each case study, the soundings input to the cloud model were taken to be representative of conditions in an area approximately two degrees of latitude on a side. Verification of the cloud tops was performed in this area. The time period considered for cloud top verification was two hours prior to and three hours after the time for which the sounding modifications were made.

For each case study site an observed sounding was chosen. It was theorized that the structure of the atmosphere in the lowest 30-40 kPa is the part of the atmosphere that is most important in determining the height of convection. Use of this assumption resulted in examination of the mean wind in the lowest 30-40 kPa. The mean wind was used to determine which rawinsonde site the air in the lowest 30-40 kPa in the verification area was closest to at 1200 GMT.

3.2 Modifications above the boundary layer

Sounding modifications above the boundary layer were made on the basis of NWS analyses, satellite photos, and minicomputer analyses that may be commonly available to a forecaster with minicomputer capabilities. The principle use of these products was to estimate temperature and mixing ratio changes associated with advection and vertical motion. Horizontal temperature and moisture advection were simulated in a sounding by extrapolating the past 12-24 h advection,

where appropriate. The vertical motions were estimated by examining the surface wind and pressure fields, 50 kPa vorticity advection, upper air analyses, and upper air forecasts. The effects of advection of moisture or temperature change of layers in the atmosphere by vertical motion were also estimated. In each case, estimates of changes above the boundary layer were made subjectively.

3.3 Boundary layer modification

The observed surface pressure was considered in boundary layer changes. These pressures varied from 89 kPa to 102 kPa, which made a difference on which pressure levels were affected by boundary layer events. Because all forecasts were for afternoon convection occurrence, low surface pressures corresponded to simulating an elevated heat source in the model.

Examination of sequences of daytime soundings taken in the boundary layer close together in time and space show rapid temporal and spatial fluctuations of both temperature and moisture. Schaefer (1975) discussed the changes of the temperature and moisture profile in the boundary layer on summer days in Oklahoma. Mahrt (1975) showed low-level vertical gradients of moisture on summer afternoons in Colorado. Examination of soundings taken during the AVE IV experiment conducted by NASA (Fucik and Turner, 1975), three to six hours apart, showed large changes of both the temperature and moisture profiles. Because of these rapid temperature and moisture fluctuations in the boundary layer, modifications in the boundary layer may be more critical in making accurate cloud top forecasts than modifications above the boundary layer.

The boundary layer was defined for modification purposes to be that layer where the air was in contact with the surface and the lapse rate was nearly dry adiabatic. The boundary layer depth was estimated to the nearest 5 kPa level by considering the intensity and duration of insolation. Kuo (1974) and Schaefer (1975) discussed unstable boundary layers over land areas that had a superadiabatic region of 10-300 m thick near the ground and depths of the boundary layers of 1000-2000 m above the ground level. These figures are compatible with the boundary layer profiles used in this study.

The observed surface temperature used for verification of the occurrence or nonoccurrence forecasts and for modification purposes was determined by looking at hourly reports of stations in the verification area starting at least four hours before height verification time. The temperature chosen was the one reported the hour prior to the observation of convection at a reporting station in the verification area. If no station in the verification area reported convection, then the temperature that appeared to be the most representative of the area was chosen. This method does not rule out the possibility that there may have been hot spots in the area that were more representative of convection-initiating conditions. Temperature forecast models and forecasters make temperature forecasts that are verified using temperatures reported at observing stations. Therefore, it was assumed that the method of determining surface temperatures discussed would yield temperatures closer to what a forecast model or forecaster would make than the temperature at localized hot spots. Surface dewpoints were determined

in a manner similar to that used for temperatures; actual forecasts of dewpoint, however, might be more difficult to make.

Furthermore, an accurate forecast of the surface dewpoint does not assure one of having a picture of the boundary layer moisture profile. Ulanski and Garstang (1978) stated that the mixing ratio at the surface was representative of the moisture supplied to the convection cells in their Florida-based experiment. Petterssen et al. (1945) reported observations that showed that the use of the surface mixing ratio value in determining cloud base height resulted in cloud bases about 300 m lower than those actually observed. They found that the mixing ratio was higher at ground level than in the rest of the boundary layer and that the mixing ratio value at 300 m was representative of the cloud base mixing ratio. Schaefer (1975) and Mahrt (1975) both showed boundary layer observations that reveal mixing ratios that decrease upward near the surface. Schaefer cited several references on theories of estimating the low-level vertical moisture distribution.

The cloud base is a very important factor in determining the resultant cloud top forecast. As discussed earlier, the 100 kPa mixing ratio is very important in the cloud top forecast. Matthews and Henz (1975) mentioned that a lower cloud base increases the potential instability and the energy for the modeled cloud by increasing the amount of latent heat released.

One of the modification techniques used required knowledge of the height of the observed cloud base. The representative cloud base height for the verification area was determined by inspecting the hourly surface observations of reporting stations. Even in situations

where the cloud base apparently should be at a uniform height, different cloud base heights were reported. The cloud base height used was the one that was most commonly reported.

In order to evaluate the various methods of estimating the vertical distribution of boundary layer moisture, four different boundary layer modifications were conducted on each sounding. These four modifications were in addition to the unmodified sounding and the sounding whose modifications were restricted to being above the boundary layer.

A listing of the names of the modifications used as model input in this study and a description of the changes made in each of the modifications is given in Table 1. For all modifications, the cloud model automatically modified the 100 kPa temperature to the convective temperature. Upper air changes, above the specified boundary layer, were made for all modifications except for those referred to as modification A. Changes in the boundary layer were made for all modifications except for those referred to as modification A and modification B. Future references to modification techniques will use the names listed in Table 1.

3.4 Cloud height forecast verification

There can be a wide range of heights of convective clouds, but radar reports containing more than one elevation or other supplementary height information occur only about one-fourth of the time. In order to determine the areal extent of the radar-reported maximum tops, enhanced IR satellite photos were used. Imagery is received from the GOES-2 geostationary satellite, providing one visible and one IR picture

TABLE 1. Names and descriptions of sounding modifications used.

Modification Name	Basic Feature	Detailed Description
A	NONE	The observed 1200 GMT sounding was used as input to the cloud model. This sounding was used for comparison purposes.
B	ABVBL	Changes were made only above the boundary layer. This modification was made to see whether upper air changes alone could improve cloud top forecasts.
C	AM	Boundary layer mixing ratio values were obtained by using the mean mixing ratio from the 1200 GMT sounding for the depth of atmosphere that later became the afternoon boundary layer. This boundary layer modification was similar to that used in computing the Lifted Index.
D	SFCTD+	The boundary layer mixing ratio values were linearly interpolated between the surface mixing ratio and the mixing ratio at the next pressure which was a multiple of 5 kPa and was above the top of the boundary layer. This was an attempt to simulate a vertical moisture gradient in the boundary layer.
E	SFCTD	This modification was like modification D except that here, the surface mixing ratio value was used through the entire boundary layer. This modification simulated a constant mixing ratio in the vertical in the boundary layer.
F	CLDBASE	The subcloud mixing ratios were set equal to the estimated cloud base level saturation mixing ratio. The cloud base temperature and pressure were used to determine the cloud base saturation mixing ratio. For this modification, cloud base elevations were taken from observations.

during each daylight hour over the eastern United States. At night, two IR photos are received each hour. From its location at 0°N, 75°W and an altitude of about 35,800 km, GOES-2 provides IR photos that have a resolution of 9 km at the satellite subpoint. For most of the area considered by this study, the resolution is about 12 km. Because of this coarse resolution, the somewhat limited enhancement capability, and other factors which can make difficult the interpretation of the IR emission that reaches the satellite, radar-measured tops were the primary data used in verification. The satellite imagery was used as a gross check to determine if a few large cells had distinctly colder tops than most of the others. When satellite imagery suggested that less than 50% of the area under consideration had tops that were more than 2 km higher than the rest, the tallest of these tops was classified as highest top and all other tops were classified as prevailing tops. It is probable that the highest cells contain the greatest amount of severe weather and vigorous convection, so they are of considerable interest.

Radar reports at the time and in the area of verification were examined. All available hourly and special reports were considered. In most cases, a height that corresponded to the prevailing coverage, as determined by the enhanced IR, repeated itself. If more than one radar reporting station covered the area, all reports were considered, but the closest station was given preference on the final height determination.

Using radar reports as verification for the model introduced many sources of error. The lifetime of a cell is often less than 30 minutes and at most, radar reports are made twice hourly. Hence, the

low frequency of observations could tend to introduce an underestimation of the cloud tops measured by radar. Not all echoes are scanned vertically by the radar observers, making it possible that other higher tops may have been present. Saunders and Ronne (1962) showed results with a 10-cm WSR-57 radar that the height of the visible top exceeds that of the radar-estimated top by 60-900 m, the error increasing with distance. Darrah (1978) discussed physical factors of weather radars that could contribute to cloud top measurement errors. Some of the error factors that could occur were: varying calibrations of different radars; differing bands used; differing model radars; beam filling considerations; and side-lobe effects.

The use of pilot reports for cloud height verification was rejected due to the relatively small amount of convective top reports available and the inaccuracies associated with them. Using the Pennsylvania State University Department of Meteorology's WSR-74C radar to allow continuous scanning of convection in the vertical was rejected on the basis that this method would still contain some of the radar measurement errors mentioned earlier, reduce the size of the sample space, and make the study very localized. Despite the many sources of possible error in the measurement and interpretation of the top reports, the combined use of radar-estimated tops and enhanced IR satellite imagery was selected as the best and most practical method of cloud top verification available.

3.5 Experimental plan

For each case study performed for this study, six different modifications were run, each with four specified cloud radii.

All case study sites used were east of 100°W over United States land areas during warm season afternoons. The results from these case studies are presented next.

4.0 EXPERIMENTAL RESULTS

4.1 Case selection

The results presented in this chapter were taken from case studies run on data from 23 days between April and August, 1978.

Approximately 65 case studies that contained prevailing tops and 55 case studies that contained highest tops were verified. About 30 case studies where no convection was observed were executed. No observed sounding was used more than once, except in two cases, even though case studies may have been associated with the same frontal system or air mass.

The convection occurrences were separated into frontal and nonfrontal categories. In section 4.5, the results of analyses of the frontal and nonfrontal categories of data are discussed. The frontal category continued approximately 27 cases for which the verification area was within 100 km of a surface front as analyzed by the NWS, all prefrontal squall line cases, cases where outflow from existing cells produced front-like conditions, or cases where convection was parallel to and moving with a front up to 100 km from the position of the surface front. All other case studies were placed in the nonfrontal category.

While it is true that there is a large number of combinations of cloud radii, boundary layer moisture specification schemes, and methods of handling the cloud physics that may yield an improved solution, the results presented are for the cloud radii and modification schemes described as run on the Anthes cloud model.

4.2 Occurrence forecasting

In addition to providing accurate cloud top forecasts, it would be desirable for the cloud model to accurately predict the occurrence or nonoccurrence of convection. This section contains the results of testing the cloud model's ability to forecast convection when the various sounding modification techniques were used.

A forecast for no convection was assumed when the forecast 2 km radius cloud top was less than 3.3 km or when the model-computed convective temperature minus the observed temperature was greater than a specified value. All other model forecasts were considered to be for no convection. This difference, called the temperature difference, arises because the model tended to underforecast the occurrence of convection when a temperature difference of zero was taken to be the criteria. This underforecasting suggests that the temperatures used as the observed temperatures may have been cooler than the temperatures actually associated with the initiation of convection or that the cause of convection was more than just surface heating and was not accurately modeled by the sounding modifications.

Table 2 contains the forecast verification results for a temperature difference of zero degrees in contingency table form. Table 2 is presented to show the categorical distribution of the convection forecasting ability of the model. As indicated by the results in Table 2, the results of modifications D and E are nearly identical. Due to the similarity in the results of these modifications, only the results of modification E will be shown or discussed in the remainder of this section.

TABLE 2. Categorical results of model forecasts of convection occurrence for each of the sounding modifications used.

Modification A

MODEL FORECAST	OBSERVED Yes	OBSERVED No
Yes	41	5
No	26	28

Modification B

MODEL FORECAST	OBSERVED Yes	OBSERVED No
Yes	33	5
No	32	27

Modification C

MODEL FORECAST	OBSERVED Yes	OBSERVED No
Yes	14	2
No	52	23

Modification D

MODEL FORECAST	OBSERVED Yes	OBSERVED No
Yes	23	9
No	43	21

Modification E

MODEL FORECAST	OBSERVED Yes	OBSERVED No
Yes	22	9
No	41	19

Modification F

MODEL FORECAST	OBSERVED Yes	OBSERVED No
Yes	25	10
No	39	15

Presented in Fig. 2 are plots of how the percentage of correct convection forecasts for each of the modifications varied when different temperature differences were allowed. For no temperature difference, the best percentage of correct forecasts was obtained by using the unmodified sounding, modification A. As the temperature difference value was increased from zero to four degrees, the percentage of correct forecasts using the unmodified sounding increased slightly while the percentage of correct forecasts for modifications B through F increased to nearly the same level as for the unmodified sounding.

The bias for convection occurrence is computed by

$$B = \frac{F}{0} \tag{6}$$

where B is the computed bias, F is the total number of convection occurrence forecasts, and 0 is the total number of occurrences of observed convection. Bias is a measure of the tendency of the forecast technique considered to overforecast or underforecast the occurrence of an event, a bias of one meaning that the forecast technique has no bias in forecasting the event. For optimal use of the cloud model to forecast convection, a technique that has a high rate of correct convection forecasts and a bias near one is desired.

In Fig. 3, plots of how the bias for convection forecasting for each of the modifications varied when the temperature difference was varied from zero through four degrees, are presented. For no temperature difference, the bias value of the unmodified sounding was the best even though it showed that the model underforecasted convection.

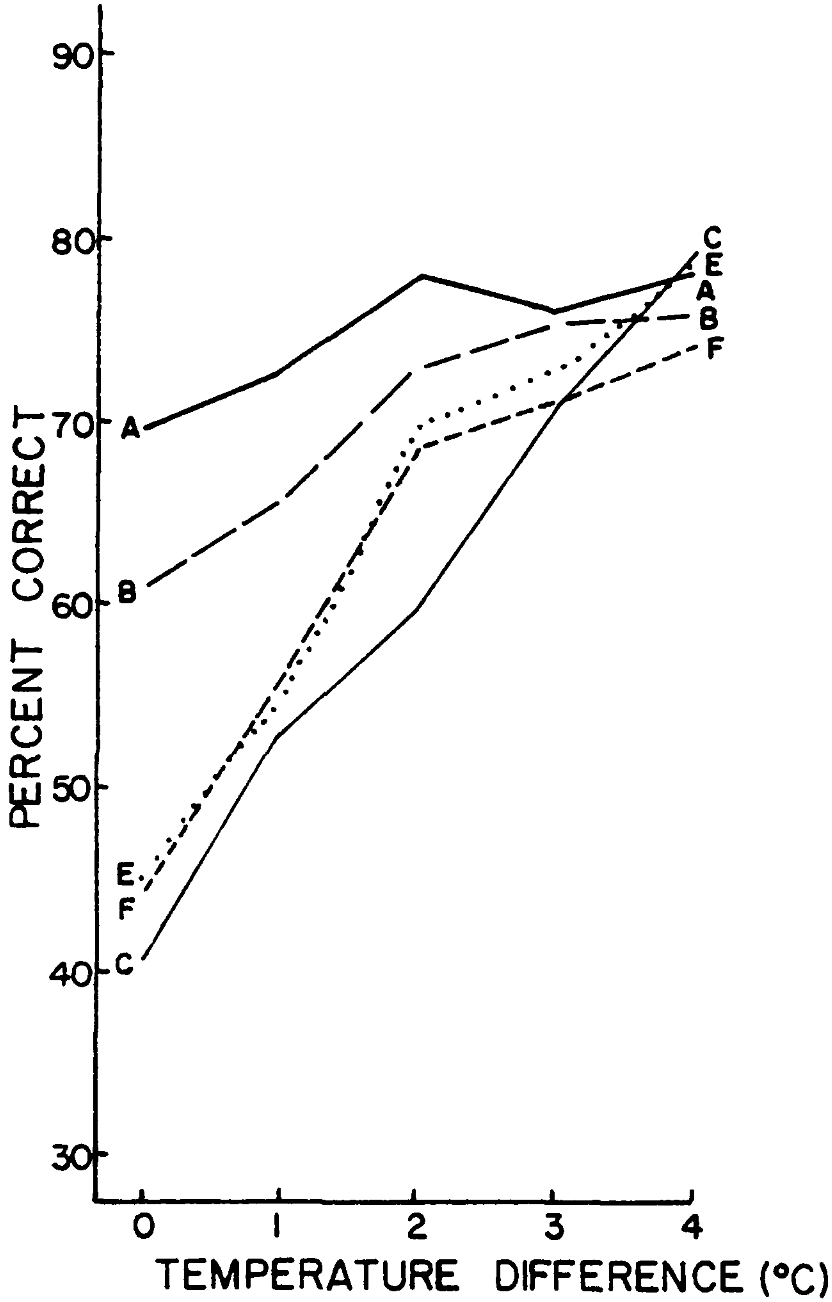

Figure 2. Percentage of correct model forecasts for convection as a function of the temperature difference (computed minus observed convective temperature) allowed for each of the sounding modifications used (see Table 1 for descriptions of modification techniques A-F).

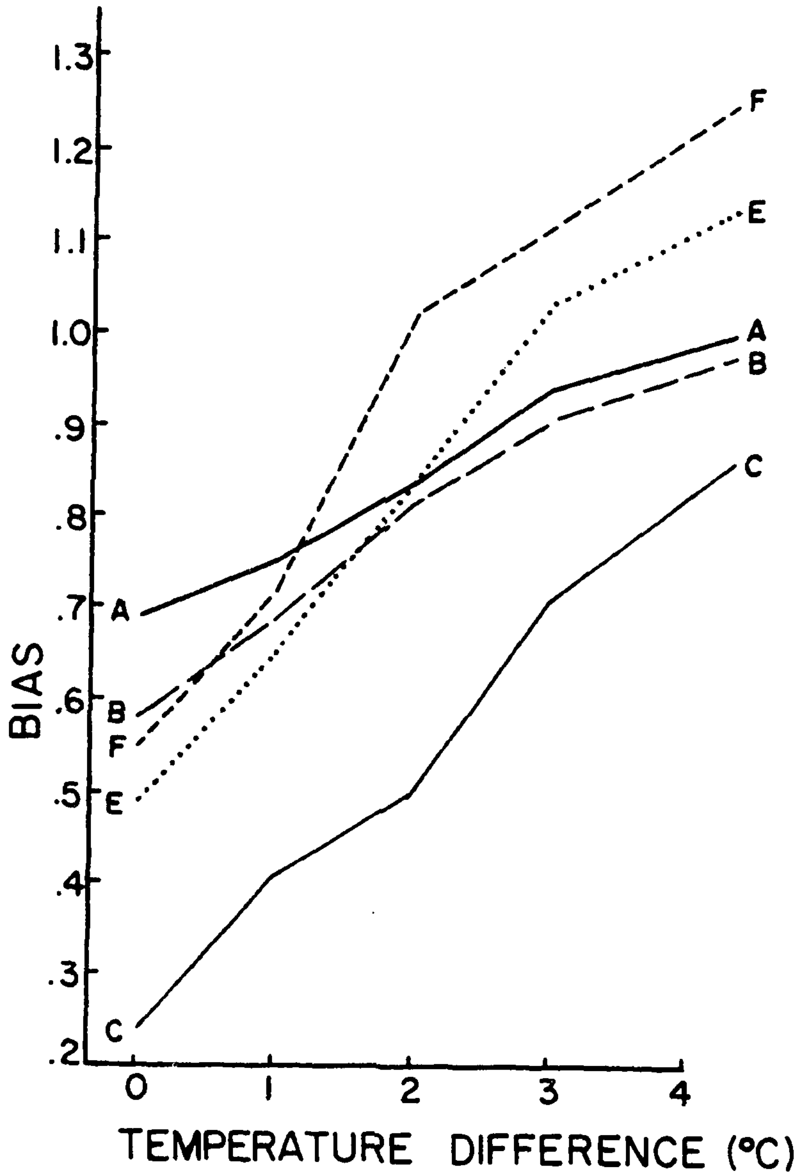

Figure 3. Bias of forecasting convection occurrence by the cloud model as a function of the temperature difference (computed minus observed convective temperature) allowed for each of the sounding modifications used (see Table 1 for descriptions of modification techniques A-F).

As the temperature difference was allowed to increase, the under-forecasting bias of the model was reduced and for some temperature and modification combinations, the bias value became greater than one. For a temperature difference of four degrees, convection forecasts of the unmodified sounding exhibited no bias.

The largest 100 kPa mixing ratios were associated with modifications E and F. Forecasts that used their higher mixing ratios resulted in overforecasting of convection occurrence as the temperature difference value was increased. It is seen in Table 3 that the lowest 100 kPa mixing ratio on the average was associated with modification C. Forecasts that used modification C always had the greatest bias toward underforecasting convection. These bias tendencies help to underscore the importance of correctly modeling the boundary layer moisture for more accurate model usage.

When a two-degree difference between computed convective temperature and the observed temperature was allowed, the occurrence or non-occurrence of convection was correctly forecast in nearly four out of five cases with little bias when the unmodified sounding, modification A, was used. The convection forecasting ability of the unmodified sounding showed a skill significant at the 0.1% level. This significance level was determined by using the Chi Square test of categorical forecasts as described in Panofsky and Brier (1968). The Chi Square test used had one degree of freedom and a null hypothesis of chance.

TABLE 3. Cloud model results relating surface mixing ratios to average subcloud depth and the average calculated depth of clouds for forecasts that used each of the sounding modification techniques and specified cloud radii of 2 and 4 km.

Modification	Average 100 kPa Mixing Ratio ($g\ kg^{-1}$)	Average Subcloud Depth (kPa)	Average Computed Cloud Depth (km)	
			R=2km	R=4km
A	14.5	15.3	9.5	11.5
B	14.3	16.2	9.4	11.7
C	13.2	20.3	8.9	11.2
D	16.0	16.2	11.2	13.2
E	16.0	16.3	11.2	13.2
F	17.9	12.9	12.2	14.2

4.3 Effects of varying cloud radius upon cloud top forecasts

Fig. 4 contains the root-mean-square error (RMSE) and average error averaged over all modifications for each of the four cloud radii used. Fig. 4 is presented to assist in determining the cloud radii that yielded the best cloud top forecasts.

Both means of error measurement indicate use of the same radius as yielding the best cloud top forecast for each category of tops. For prevailing tops, using a radius of 2 km appeared to be the best choice. For highest tops, the best forecasts were obtained by use of larger radii of 4 and 8 km as would be expected from physical considerations. In the environment, larger radii cells have larger central cores that are less susceptible to the entrainment of environmental air than the central cores in smaller radii cells. These larger cells generally are able to grow to greater heights than

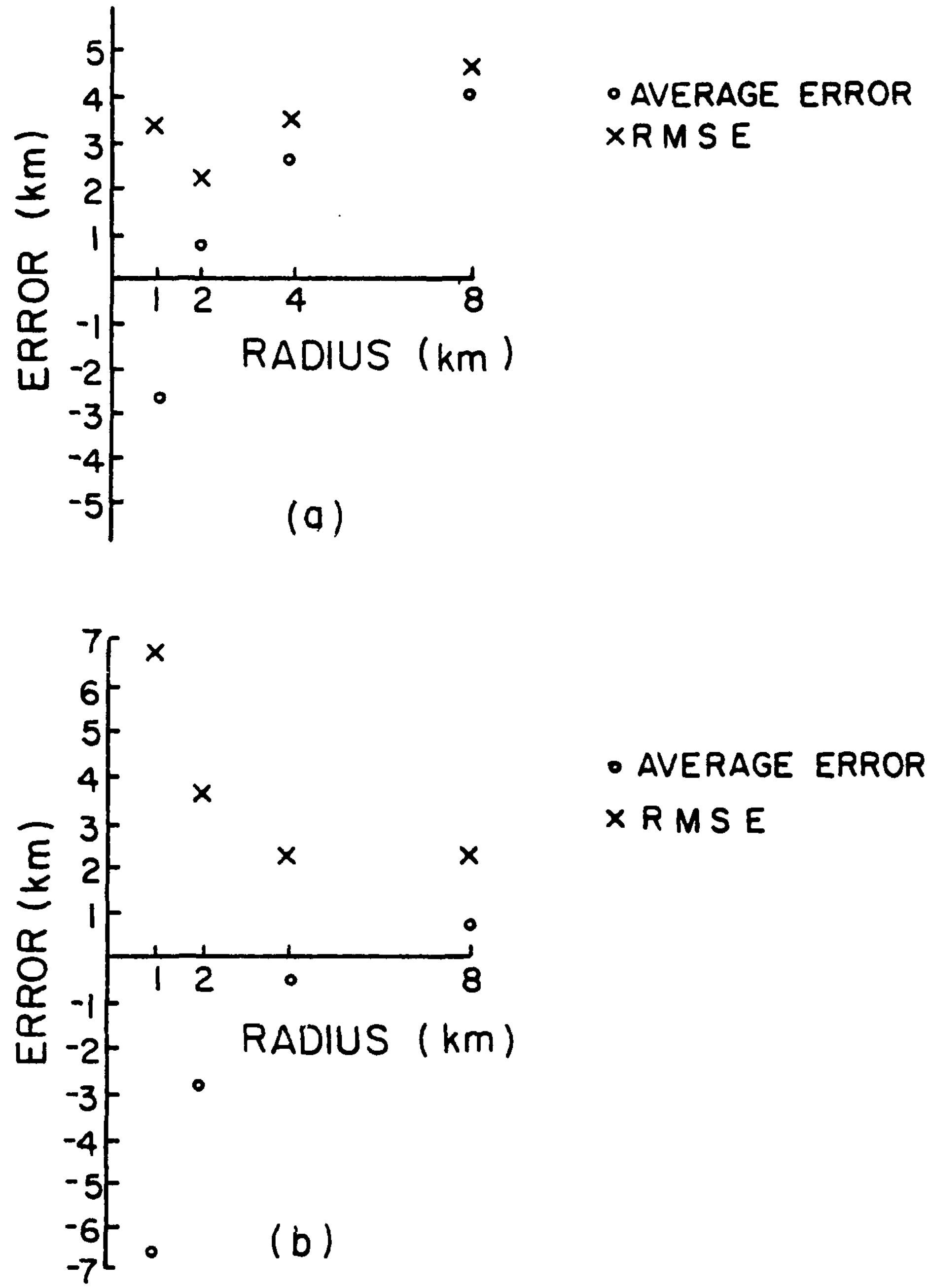

Figure 4. Cloud top forecast errors averaged over all sounding modifications as a function of cloud radius for (a) prevailing tops and (b) highest tops.

the smaller cells. This effect of entrainment is parameterized in the model by defining entrainment to be inversely proportional to the specified cloud radius. The effects of entrainment can be seen in Fig. 4 as the average error for both prevailing and highest tops grew from negative to positive values as the cloud radius was increased. The average error reached zero at a much larger cloud radius for the highest tops than for the prevailing tops.

4.4 Interaction results

The 100 kPa mixing ratio is important in determining the cloud base and cloud top forecast. The sensitivity of the model forecasts to 100 kPa moisture is revealed by the results in Table 3. Lower average subcloud depths and deeper clouds were generally forecasted when higher 100 kPa mixing ratios were used by the model.

Results of forecasts obtained by using modifications D and E are shown in Table 3 to be nearly identical. The similarity was a result of the same 100 kPa mixing ratio being used by both modifications. The boundary layer moisture was handled differently in the two modifications. However, the average subcloud depth of forecasts using the two modifications was slightly greater than the average depth of the boundary layer input to the model. Since all mixing ratio values between 100 kPa and the cloud base are essentially ignored by the model in computing the cloud top, on the average, the data used by the model was the same when either modification D or E were used. Due to the similarities of the results of the two modifications, the results of modification D will not be given or discussed in the remainder of this chapter.

4.4.1 Prevailing top forecast results

The RMSE were computed for forecasts using all modification and radius combinations for prevailing tops and plotted in Fig. 5. The modification used by the model that produced the smallest RMSE for prevailing tops, as shown in Fig. 5, was modification C and a radius of 2 km. The RMSE of modification C and a radius of 2 km in Fig. 5 is not much less than that of the other modifications with a 2 km radius. In general, except for the RMSE of modification F, the RMSE of the modifications are lower with a radius of 2 km than for other radii as discussed earlier. Forecasts obtained by using modification C had a negative, underforecasting, bias of only 0.3 km (Fig. 6). Modification C had the lowest average absolute error (1.4 km) and RMSE (2.0 km) of all radii and modifications used. It is this method of averaging the boundary layer moisture that meteorologists often use in determining the LCL. However, the average computed subcloud depth of 20.3 kPa obtained when modification C was used, as shown by Table 3, appears to be an unrealistically large depth. By comparison, the cloud base of modification F, which was specified by observations, was 13 kPa (Table 3). Thus, the average subcloud depth using modification C was apparently 7 kPa too deep, which shows that the convective cloud forecasts obtained by using modification C were not a very close approximation to what was observed in the atmosphere.

The RMSE for forecasts obtained by using modifications C and E and a radius of 2 km were virtually the same even though the bias of modification E was 1.5 km and the bias of modification C was 0.3 km (Fig. 6). To explore the possibility that with the bias removed forecasts using other modifications might produce more consistent results

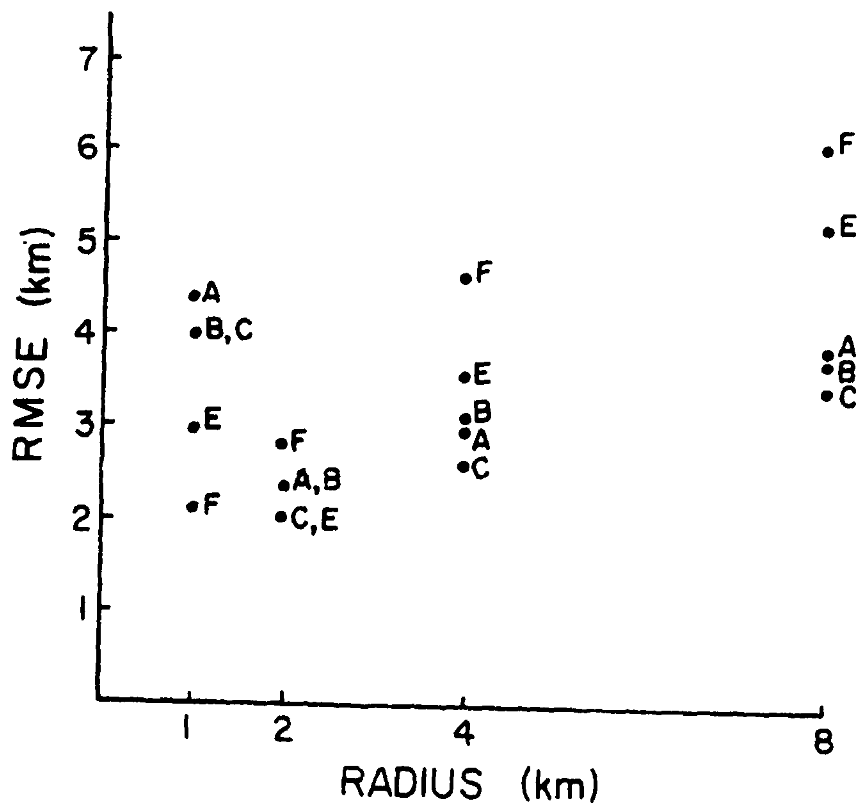

Figure 5. RMSE of prevailing top forecasts as a function of cloud radius for each of the sounding modifications used (see Table 1 for descriptions of modification techniques A-F).

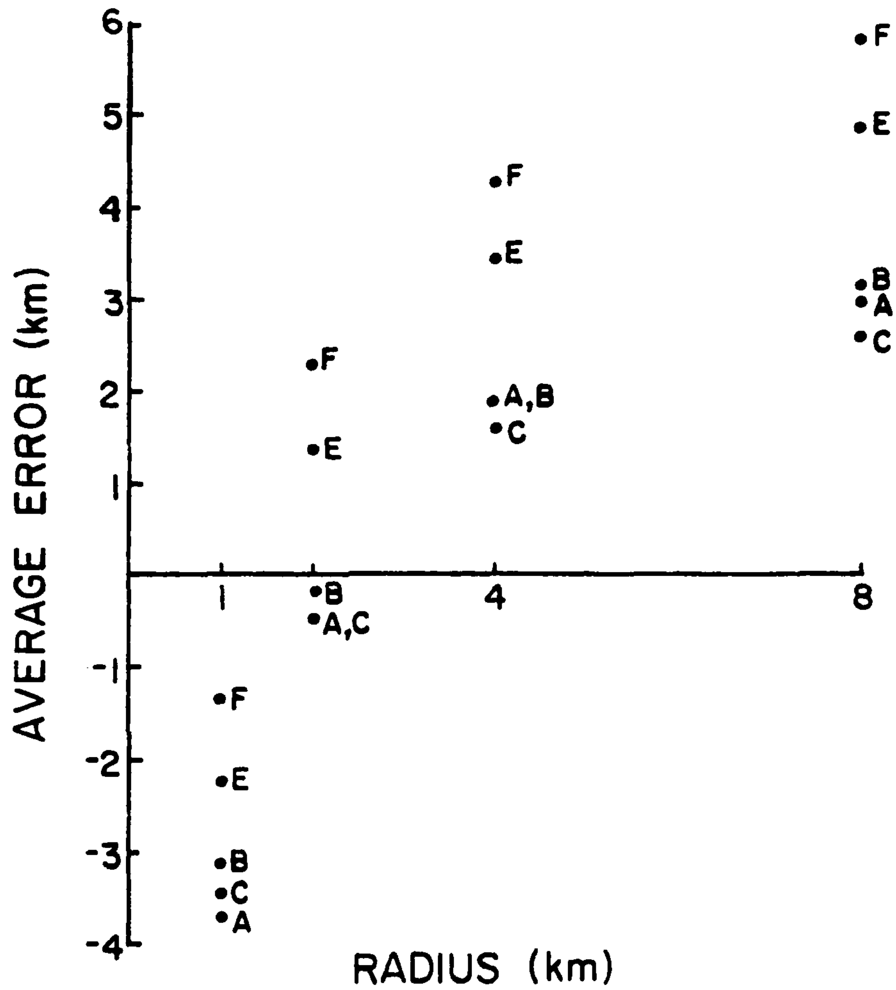

Figure 6. Average error of prevailing top forecasts as a function of cloud radius for each of the sounding modifications used (see Table 1 for descriptions of modification techniques A-F).

than modification C, a technique for computing RMSE with the bias removed was used.

The unbiased RMSE can be calculated (Panofsky and Brier, 1968) by

$$RMSE_{un} = [(RMSE_b)^2 - (Bias)^2]^{1/2} \tag{7}$$

where $RMSE_{un}$ is the resultant unbiased RMSE, $RMSE_b$ is the biased RMSE, and Bias is the average error. The result of applying (7) to the values used to plot Figs. 5 and 6 yielded the values in Fig. 7. Shown in Fig. 7 are what the RMSE would be if the bias were removed. The unbiased RMSE are much smaller in general than the biased RMSE. This bias removal in practice could only be done once a large enough number of case studies were considered in order to be sure that the bias used was similar to that of the entire population of convective cloud tops.

The ratio of the larger to the smaller variances can be tested using the F-test (Panofsky and Brier, 1968) to see whether the variances differ from each other by a significant amount. To test whether bias removal for modification E and a radius of 2 km would result in significantly better forecasts than modification C and a radius of 2 km, the F-test was used. The F-test showed that modification E and a radius of 2 km had an unbiased RMSE that was significantly better, at the 5% confidence level, than the unbiased RMSE of modification C and a radius of 2 km. Modification E and a radius of 2 km should be used with a larger sample space in future

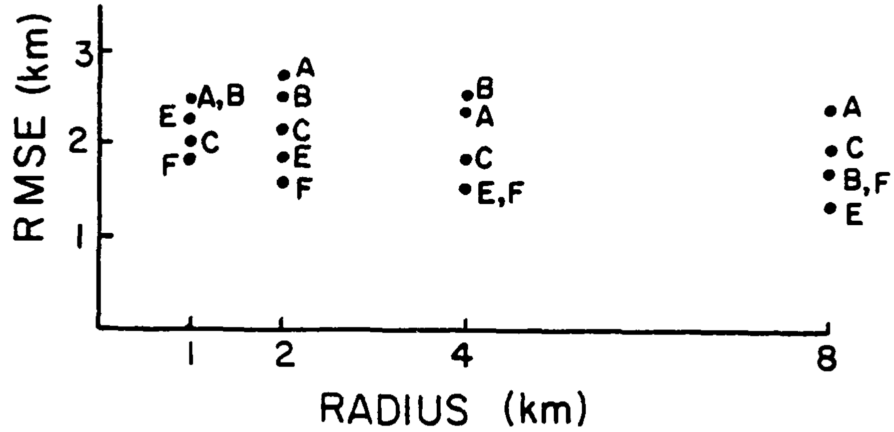

Figure 7. Theoretically-determined unbiased RMSE of prevailing top forecasts as a function of cloud radius for each of the sounding modifications used (see Table 1 for descriptions of modification techniques A-F).

work to learn if its use could produce more consistent forecasts than using modification C and a radius of 2 km.

Interaction by the forecaster to the input sounding appears to improve the model's ability to forecast prevailing tops when bias is removed. For all cloud radii used, all sounding modifications had a lower unbiased RMSE than the unmodified sounding (Fig. 7).

It is interesting to note that generally the RMSE for modification B were very similar to the RMSE of the unmodified sounding while the RMSE of modifications C through F were much lower than those of the unmodified sounding. The difference between modification B and modifications C through F was in the boundary layer. Apparently, forecasts using the 1200 GMT temperature and moisture profile in the boundary layer was the factor that determined the lack of sounding representativeness for use by the cloud model.

While it is likely that the use of modification E might result in more consistent forecasts than modification C, a plot of the model-forecast prevailing cloud tops using modification C versus radar-observed cloud tops is presented in Fig. 8. An accuracy envelope of $\pm$1.5 km about the perfect forecast line is indicated. The value of 1.5 km was chosen to represent the inaccuracies of radar measurement and the original desired goal for forecasting accuracy. Sixty-nine percent of the data plotted in Fig. 8 had forecast tops that were within 1.5 km of the observed tops. The 21 case studies with a forecast error of more than 1.5 km as shown in Fig. 8 were examined individually. These 21 case studies had no obvious properties that would allow them to be identified before verification time.

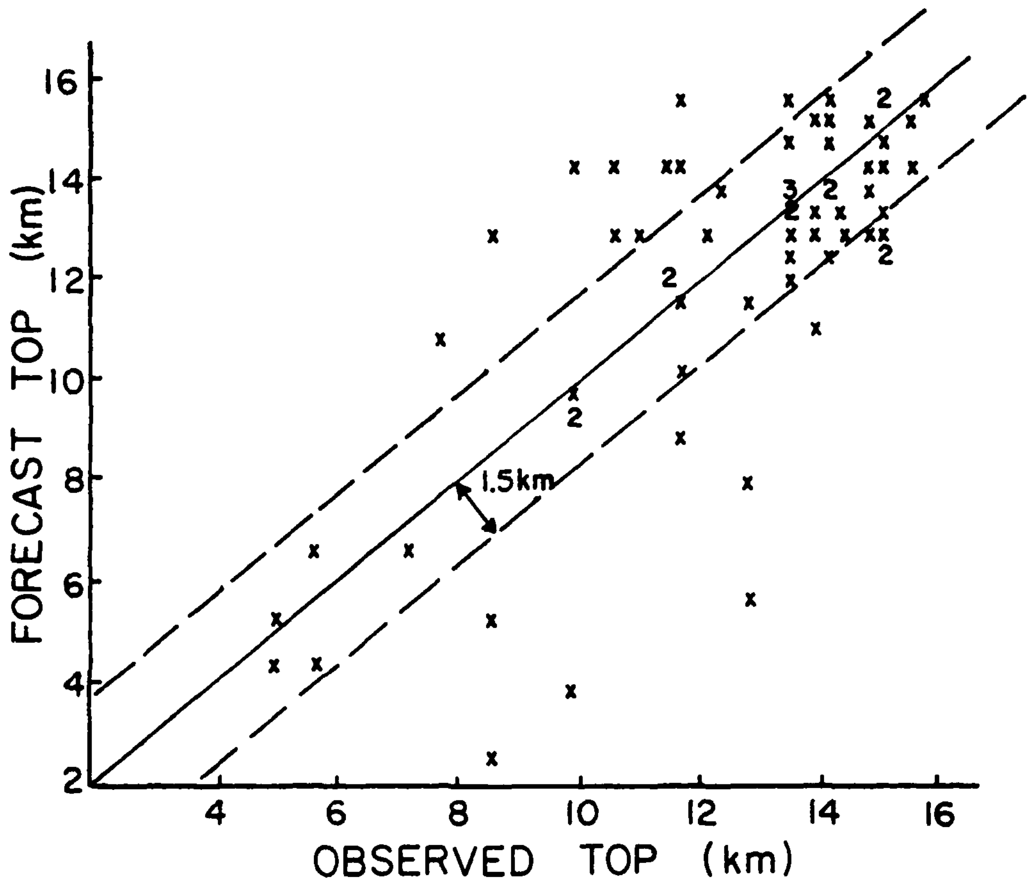

Figure 8. Predicted prevailing tops (modification C, radius 2 km) versus radar-estimated observed tops. Long dashes represent errors of 1.5 km.

4.4.2 Highest top forecast results

The highest top error analysis is shown in Figs. 9 and 10. The better forecast combinations for highest tops tended to have larger radii than for prevailing tops. Larger radii clouds in the model have less entrainment of air into the cloud parcel. This is similar to the reduced effects of entrainment with increased cloud radius observed in the environment. Figs. 9 and 10 show that the most consistent and accurate cloud top forecasts for highest tops were produced by forecasts that used modification E and a radius of 4 km.

Fig. 11 shows that overall, the unbiased RMSE of forecasts obtained by using modifications E or F with a cloud radius of 4 km and modification E and a radius of 8 km appeared to produce the lowest unbiased RMSE. The unbiased RMSE of modification F are similar to those of modification E. But, forecasts of cloud base heights as required for modification F are more difficult to make than the forecasts of surface dewpoints for modification E. Hence, modification E is preferable over modification F.

Forecasts obtained by using modifications E and F which had higher 100 kPa mixing ratios tended to result in better forecasts of highest tops than forecasts obtained by using modification C. This tendency could be the result of the model simulating the ability of parcels originating near the surface to conserve their surface mixing ratios during ascent through the subcloud layer. In an observational study, Ulanski and Garstang (1978) found that the intensity of a convective storm as measured in terms of the amount of rain produced is directly proportional to the horizontal area

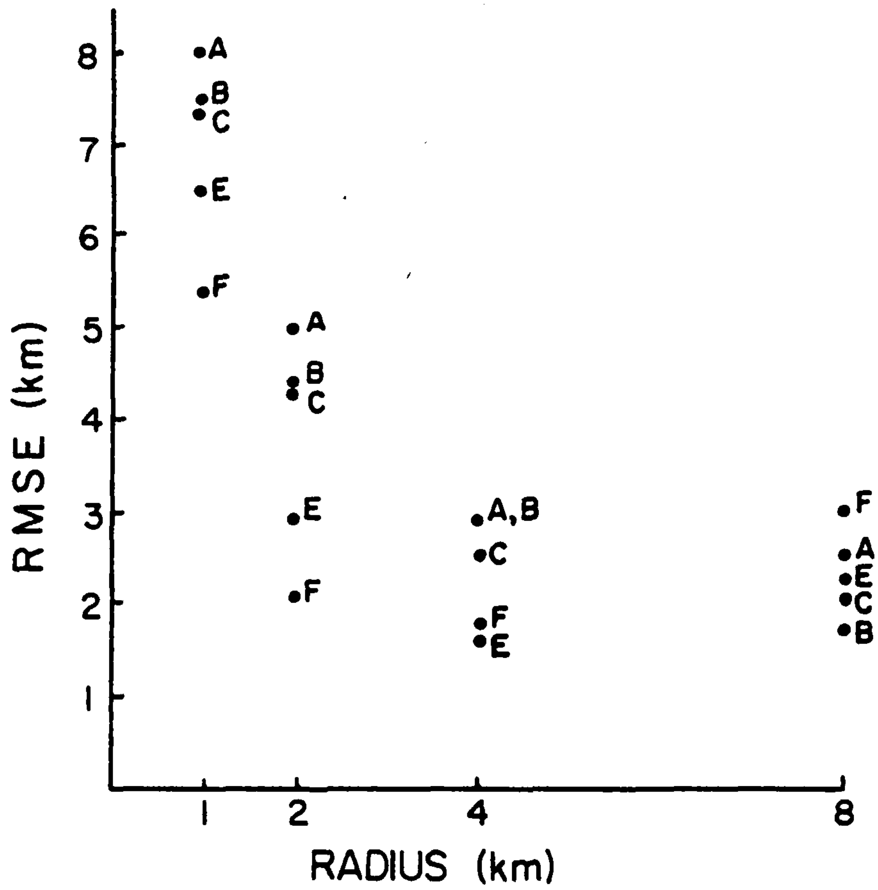

Figure 9. RMSE of highest top forecasts as a function of radius for each of the sounding modifications used (see Table 1 for descriptions of modification techniques A-F).

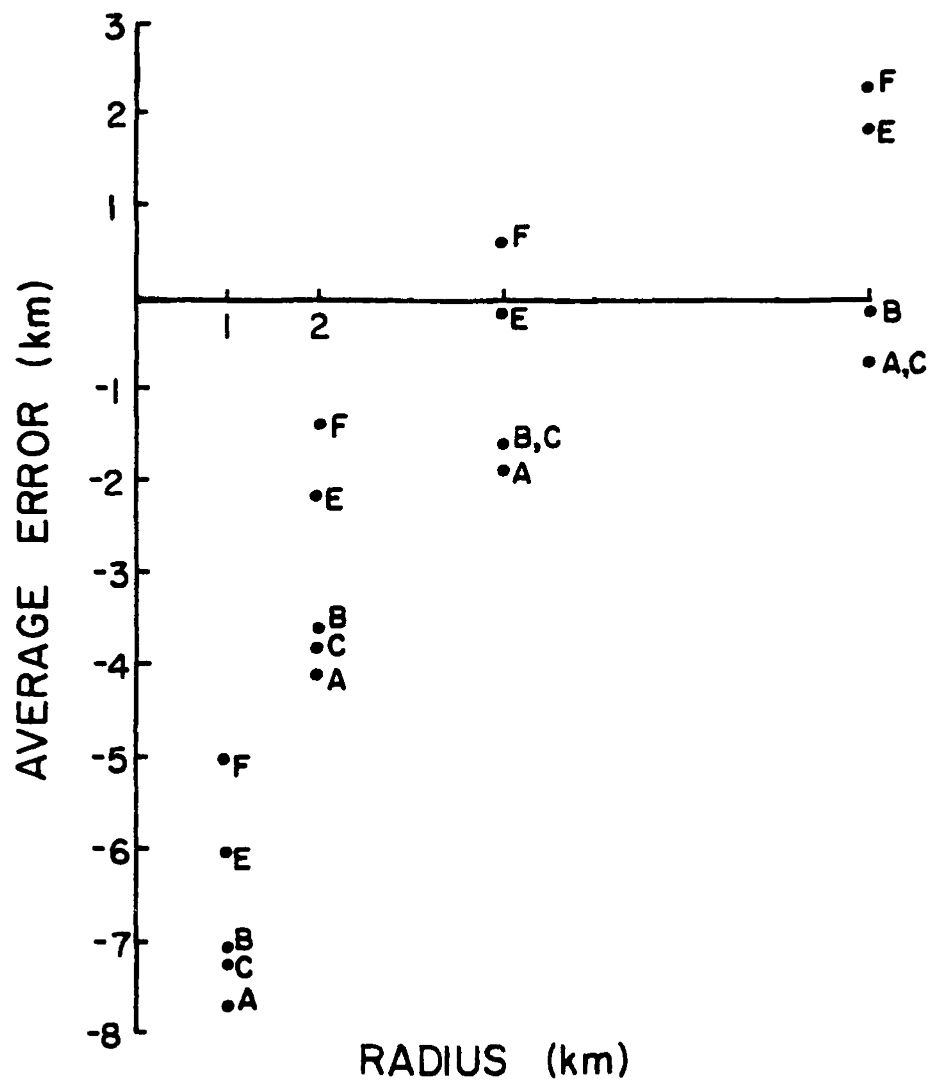

Figure 10. Average error of highest top forecasts as a function of cloud radius for each of the sounding modifications used (see Table 1 for descriptions of modification techniques A-F).

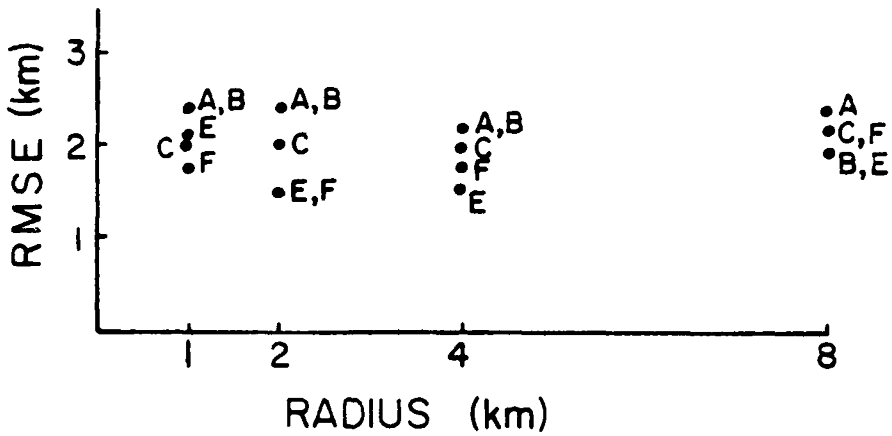

Figure 11. Theoretically-determined unbiased RMSE of highest top forecasts as a function of cloud radius for each of the sounding modifications used (see Table 1 for descriptions of modification techniques A-F).

covered by surface convergence. The increased area of low-level convergence associated with highest tops may allow parcels reaching the cloud base to experience less entrainment of drier air in the subcloud layer than in the case of prevailing tops.

Fig. 12 shows the plot of the forecast highest cloud tops for forecasts obtained by using modification E and a radius of 4 km versus radar-observed tops. Seventy percent of the data plotted in Fig. 12 had forecast tops that were within 1.5 km of the observed tops. There are 16 case studies with a forecast error of more than 1.5 km. Only three of these case studies were not associated with large-scale forcing such as positive vorticity advection at 50 kPa, a surface front, or cyclonically-curved isobars. However, the model handled other similar cases well. So, as with prevailing tops, no pattern was present that would identify a poor forecast before verification time.

4.5 Comparison of results from frontal and nonfrontal cases

In an attempt to investigate the sources of error in the model results, as well as to study further the merits of interaction, the convection cases were stratified into frontal and nonfrontal categories. These were differentiated according to the definitions in section 4.1; it should be kept in mind that frontal convection was allowed to include certain patterns of convection ahead of fronts.

The sample from which these results were computed was relatively small. Hence, the results, especially those of the theoretically-determined unbiased RMSE, should be considered to be possible indicators of the situations where interaction could be beneficial.

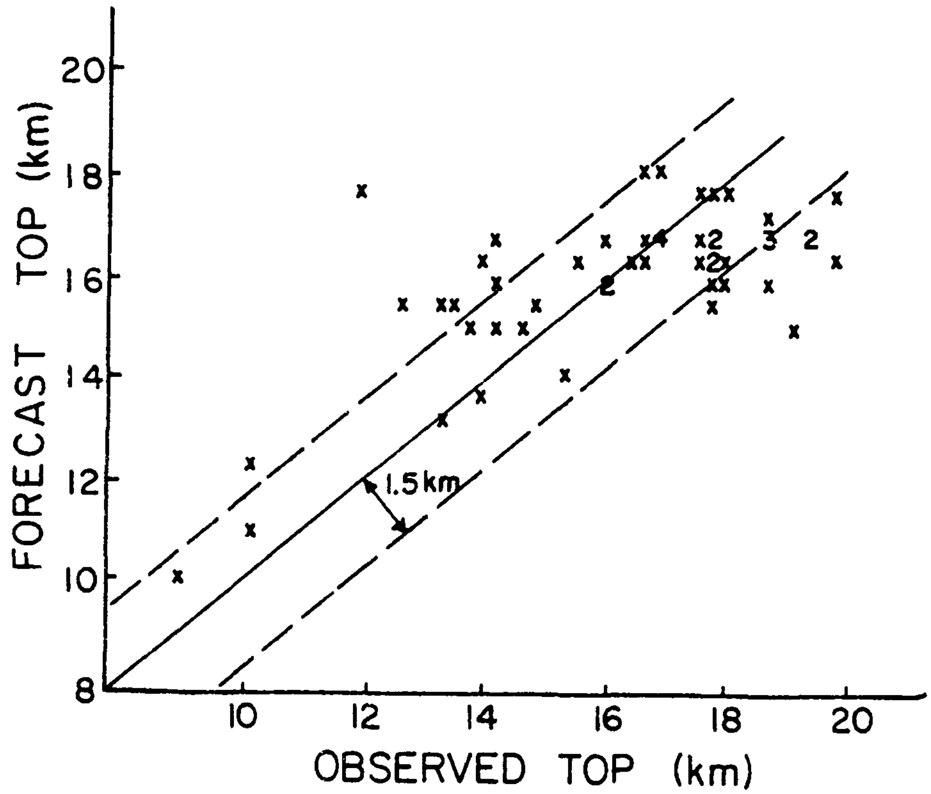

Figure 12. Predicted highest tops (modification E, radius 4 km) versus radar-estimated observed tops. Long dashed lines represent errors of 1.5 km.

The results which are discussed in the remainder of this section are summarized in Table 4.

The nonfrontal cases of convection were considered first. For nonfrontal cases of prevailing tops, the lowest RMSE for 39 case studies was that of modification C and a radius of 2 km, just as was true of the total sample discussed in section 4.4.1. The lowest nonfrontal RMSE for the unmodified sounding, modification A, was with a radius of 2 km. The F-test showed that the RMSE of these two modifications were not significantly different at the 5% confidence level. When nonfrontal highest tops were examined, the lowest RMSE for 29 case studies was that of modification E with a radius of 4 km, just as with the total sample. The lowest nonfrontal RMSE for the unmodified sounding was with a radius of 8 km. The F-test showed that these two RMSE were not significantly different, at the 5% confidence level, as was the case for the prevailing tops.

However, when correction for bias was made, interaction appeared to produce some benefits. The lowest unbiased RMSE for prevailing tops was obtained by using modification E and a radius of 4 km. The corresponding lowest RMSE of the unmodified sounding was with a radius of 1 km. These RMSE were significantly different, at the 5% confidence level. For the highest tops, the lowest RMSE was that of modification E and a radius of 4 km, as with the total sample, while the lowest RMSE of the unmodified sounding was with a radius of 8 km. The F-test showed that these RMSE were significantly different at the 5% confidence level.

The RMSE for 27 frontal situations were considered separately from the nonfrontal situations. The lowest frontal RMSE for prevailing

TABLE 4. Results of F-tests for significant differences between the lowest RMSE of the modified soundings and the lowest RMSE of the unmodified sounding for various stratifications of case studies

			F-TEST RESULT	
Stratification Category	Approximate Sample Size	No Difference At 5% Confidence Level	Modified Sounding RMSE Significantly Better at 5% Confidence Level	Modified Sounding RMSE Significantly Better at 1% Confidence Level
NONFRONTAL				
Prevailing Tops Biased RMSE	39	X		
Highest Tops Biased RMSE	29	X		
Prevailing Tops Unbiased RMSE	39		X	
Highest Tops Unbiased RMSE	29		X	
FRONTAL				
Prevailing Tops Biased RMSE	27			X
Highest Tops Biased RMSE	25			X
Prevailing Tops Unbiased RMSE	27			X
Highest Tops Unbiased RMSE	25	X		

tops was obtained when modification E and a radius of 2 km were used and the lowest RMSE for the unmodified sounding was obtained when a radius of 2 km was used. The F-test showed that the RMSE of these two modifications were significantly different at the 1% confidence level - the modified sounding's RMSE was significantly lower than the RMSE of the unmodified sounding. For highest tops, the lowest frontal RMSE, modification E and a radius of 4 km, and the lowest RMSE for unmodified soundings, with a radius of 8 km, were compared. The F-test showed that they were significantly different at the 1% confidence level. As with prevailing tops, interaction appeared to improve the forecasts.

Estimates of the unbiased RMSE in frontal situations were also computed. For both prevailing and highest cloud tops, the lowest unbiased RMSE was obtained by using modification E and a radius of 4 km. Also, for both prevailing and highest cloud top forecasts, the lowest RMSE for the unmodified sounding was when a radius of 1 km was used. For prevailing tops, the lowest RMSE of modification E was significantly lower, at the 1% confidence level, than the lowest RMSE of the unmodified sounding. However, for highest tops, these RMSE were not significantly different at the 5% confidence level. The RMSE of the unmodified sounding and a radius of 1 km was mostly a function of the underforecasting bias. Hence, the results for highest tops may have been more of a function of the small sample space than of the possible lack of benefit of sounding interaction.

In general, it can be concluded that forecasts that were obtained by use of modified soundings were not significantly different, at the

1% confidence level, from those obtained by use of unmodified soundings in nonfrontal cases of convection. However, for frontal cases this was not true. Use of the modified sounding for cells in the vicinity of fronts resulted in cloud top forecasts that generally had RMSE that were significantly better, at the 1% confidence level, than forecasts obtained by use of unmodified soundings. Thus, within the limitations of the experiments discussed here, sounding modification should not be rejected as an option. However, further experiments with an unbiased model will be desirable and necessary to establish this result firmly.

The higher RMSE of the unmodified sounding in frontal situations makes physical sense. Often in nonfrontal warm season situations, the winds at all levels are light, the atmosphere is nearly barotropic, there is little large-scale vertical motion, and there is an absence of large-scale temperature and moisture advection. These nonfrontal conditions allow the sounding in an area to remain relatively unchanged over a 12 h period when compared to frontal situations.

It was from the weakness of model forecasts using the unmodified sounding in frontal situations that the need for sounding interaction for accurate cloud top forecasting becomes more apparent. This appears to be true for predictions of both prevailing and highest tops.

4.6 Review of computed vertical velocities

One of the cloud model outputs is the vertical velocity of the cloud parcel at each computational level. In this study, vertical velocities were not measured, compared with reports of gusty surface

winds associated with convection, or used in any comparison or verification scheme. However, one way to better understand if the model is representing events in the atmosphere correctly is to look at its computed vertical velocities.

Ludlum and Scorer (1953) cited observations made during the Thunderstorm Project in the late 1940s that maximum vertical velocities of about 10 to 25 m s^{-1} were observed at heights of 3.3 km to 8 km, in clouds which mostly reached above 11 km and occasionally reached 16 km. Barnum et al. (1970) cited 1962 observations reported by Steiner and Rhyne of updraft velocities in excess of 60 m s^{-1} in severe thunderstorms which was similar to an observation reportedly made by Sinclair (Hane, 1974) for the National Severe Storms Laboratories. Adler and Fenn (1978) used satellite information to find a mean maximum vertical velocity of 29 m s^{-1} for their sample of convection occurrences.

Fig. 13 shows the average computed maximum vertical velocities for all modifications with convection occurrence. Fig. 13 shows another example of the dependence of the model results on the boundary layer moisture specification with higher 100 kPa mixing ratios resulting in higher maximum vertical velocities. As expected, the maximum vertical velocities increase with increasing cloud radius. The 2 km cells had average maximum vertical velocities near the mean maximum vertical velocity that Adler and Fenn (1978) found and the 4 and 8 km cells had vertical velocities near those associated with severe thunderstorms.

Fig. 14 shows the relationship of the computed maximum vertical velocity with the computed cloud top for forecasts obtained by using

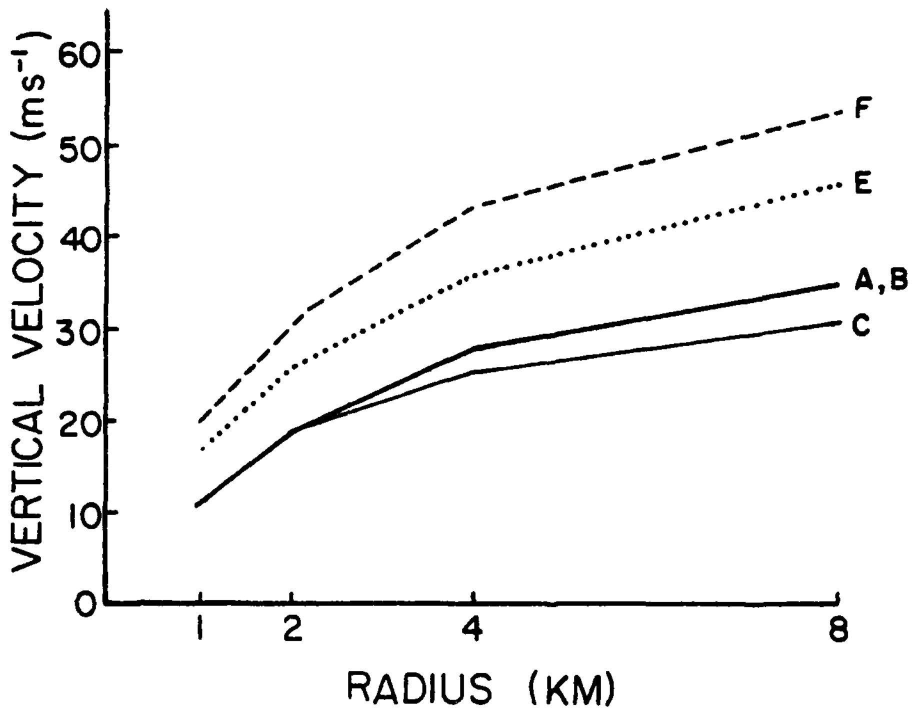

Figure 13. Maximum vertical velocity as a function of cloud radius averaged for each sounding modification used (see Table 1 for descriptions of modification techniques A-F).

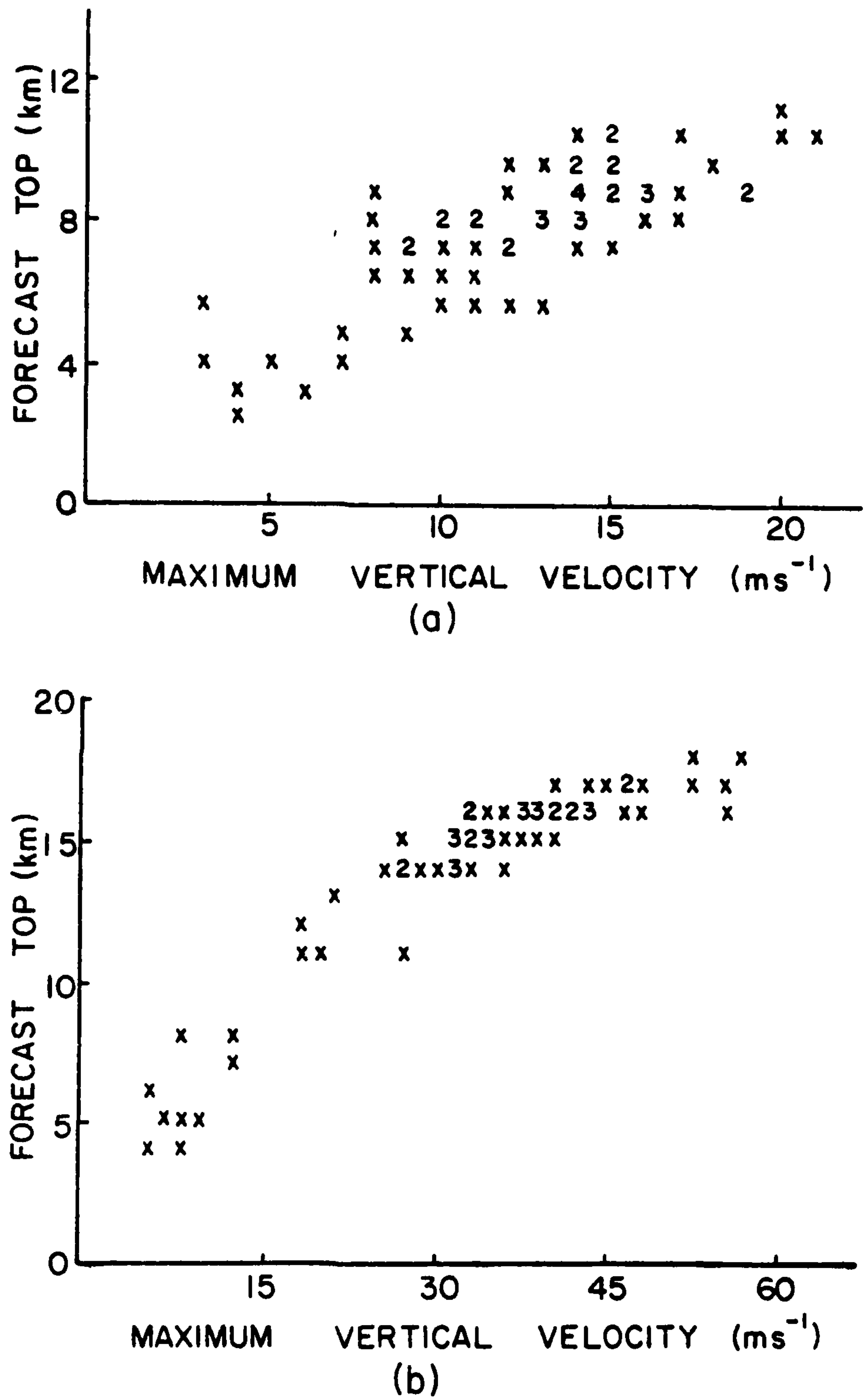

Figure 14. Predicted cloud top elevation versus computed maximum vertical velocity for a cloud radius of (a) 1 km and (b) 8 km from all forecasts obtained by using modification E.

modification E and is similar to the relationship for all other modifications. For each modification, the data appeared to go from a linear (Fig. 14 (a)) to a parabolic (Fig. 14 (b)) relationship as the cloud radius was increased from 1 km to 8 km. This relationship change was a result of the smaller radii cells generally not reaching the tropopause while the larger radii cells, with large vertical velocities, generally did. For the smaller cells, the greater their maximum vertical velocity, the higher they were able to grow. For the larger cells, the large vertical velocities helped them grow to the tropopause. At the tropopause, all of the cells had their growth stopped rapidly. So the larger cells had a physical limit as to how tall they could grow, resulting in the parabolic shape of the data in Fig. 14 (b).

Fig. 15 shows an example of the history of the computed vertical velocity of a parcel when sounding modification E was used. This example is fairly representative of the computed vertical velocity profile commonly observed.

The 4 km, and especially the 8 km cells, had their maximum vertical velocity occur much higher in the cloud than the 1 and 2 km cells did. The larger cells developed more kinetic energy and were not as susceptible to dry layers and stable layers as the smaller radii cells were. In large convection cells, the buoyancy acceleration term decreased to large negative values as the parcel became negatively buoyant and growth above the level of maximum vertical velocity ended quite rapidly.

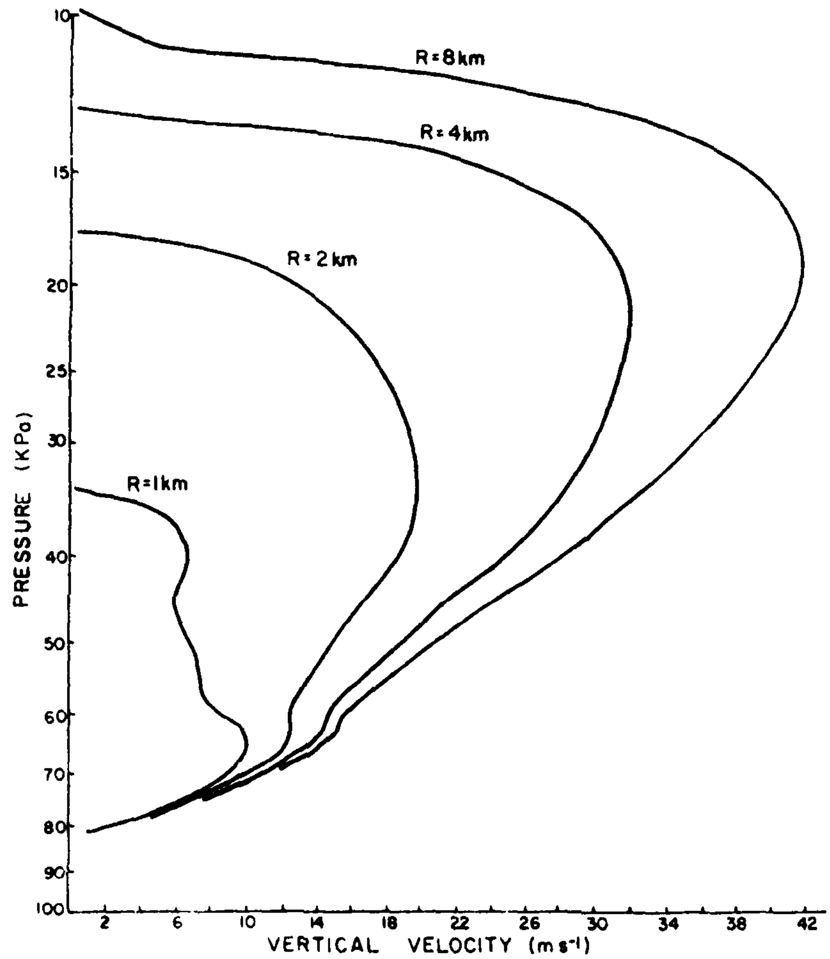

Figure 15. Vertical motion profile for various cloud radii calculated from the same sounding.

4.7 Pilot study of bias removal from cloud top forecasts

One approach to improving the accuracy and reliability of cloud top forecasts is to add an empirically-determined bias factor to each forecast. This factor could be determined only after developing a very large set of dependent observations. The modest data set used for this study was not sufficient to make any firm bias factor decisions. However, if the empirically-determined bias factors were the same as those of the population from which the sample came, the results of this pilot study and the theoretically-determined unbiased RMSE calculated earlier would be identical.

For this pilot study, the data set was randomly broken into two sets: (1) The first to determine the bias factor; (2) A second set to test the bias correction on an independent set of data. The first set of data was used to determine the bias factor when sounding modifications C and E were used in forecasts for prevailing and highest tops for all cases of convection. These modifications were selected for this pilot study because forecasts obtained by using modification C appeared to yield the best prevailing top forecasts when considering biased results and forecasts that used modification E appeared to be able to yield better unbiased results. For highest tops, the best predictor with or without bias removal appeared to be forecasts obtained by using modification E. This pilot study was a check to see whether the RMSE of modification E could be reduced with bias removal.

With the bias removed, for prevailing tops, the RMSE of modification E for all radii were at least as small as the lowest RMSE of modification C. The RMSE of modification E for prevailing and highest tops were lowered by bias removal as hypothesized. All RMSE

of modification E for highest tops with the bias removed were lower than the RMSE of modification C with the bias removed.

These findings from the developmental sample tend to support the suggestion in section 4.4.1 that bias removal would reduce the RMSE of modification E for prevailing tops and make it the best and most reliable forecaster of prevailing tops.

5.0 SUMMARY AND CONCLUSIONS

In this study the usefulness of running a cloud model on a minicomputer with the capability of allowing forecaster interaction has been studied. The input data to the cloud model were observed soundings. Radar reports and enhanced infrared satellite imagery were used for verifying the observed convective cloud tops.

The one-dimensional cloud model (Anthes, 1977) was run on a PDP-11/34 minicomputer. Vertical motion is governed by thermal buoyancy, condensate drag, and entrainment drag. The model has data input points at 5 kPa intervals from 100 kPa to 5 kPa. The temperature and/or mixing ratio at any of the 5 kPa interval levels can be interactively changed by the forecaster.

Only afternoon warm season convective activity from April through August, 1978, was considered for this study. All simulations of environmental changes not represented in the input sounding were input to the model based on subjective meteorological reasoning simulating real-time conditions. However, concurrent surface observations were available to the forecaster, so that boundary layer changes were equivalent to those that might be produced by an excellent short-range forecasting method.

For each case study, five modifications of the observed 1200 GMT sounding were run in addition to the observed 1200 GMT sounding. These modifications were designed to test whether interaction improved cloud top forecasts when convection occurs. Inasmuch as the model forecasts depend heavily on boundary layer moisture conditions, some insight was gained as to which of the various theories on boundary layer moisture were best suited for this model. Also, for each

modification and case study, solutions for cloud radii of 1, 2, 4, and 8 km were found. The convective cloud tops were broken into two groups. One group, prevailing tops, was defined to contain the prevailing top in a verification area of about two degrees of latitude on a side. The other group, highest tops, was defined to contain the highest cells which towered at least 2 km above the prevailing cloud tops in a verification area.

The predictive capabilities of convection occurrence or non-occurrence by the model were modest. When the observed convective temperature was used as the convection temperature, all forecasts obtained by using the various sounding modifications underforecast convection occurrence. The best predictions, forecasts based on the unmodified sounding, had a percent correct score of 69%. As the difference between the computed and observed convective temperature was increased, the model's underforecasting of convection was reduced and the percent of correct forecasts increased. Allowing the computed convective temperature to be two degrees greater than the observed convective temperature, forecasts that were based on the unmodified sounding provided correct convection occurrence or nonoccurrence forecasts in nearly four out of five case studies with little under-forecasting bias. Sounding modification was not as important in the case of forecasting the occurrence of convection as it was in forecasting cloud tops.

Results from the developmental sample used showed that prevailing tops are best predicted by modified soundings using the average mixing ratio in the boundary layer and a specified cloud radius of 2 km. The error values for this technique for 67 cases were: average error

-0.3 km; mean absolute error 1.4 km; and root-mean-square error 2.0 km. However, forecasts obtained by using this modification resulted in too high of an average cloud base. To make the model more realistic and possibly more reliable, the sounding modification using the afternoon surface dewpoint temperature throughout the whole boundary layer and a specified cloud radius of 2 km should be considered for possible use.

For highest top forecasts, which correspond to supercells and multicells, forecasts based on the modification using the observed afternoon surface mixing ratio through the entire boundary layer and a specified cloud radius of 4 km were the best. The error values for this technique for 53 cases were: average error -0.1 km; mean absolute error 1.3 km; and root-mean-square error 1.6 km.

The error values found in this study are comparable, though slightly greater than those of other workers using more sophisticated models and having supplementary observations such as soundings and aircraft reports available to them.

The model represents events in a realistic way. Higher tops are forecast by the larger radius cells where the effects of entrainment of environmental air are reduced. As appears to be the case in the atmosphere, the cloud model is much more sensitive to temperature and moisture changes in the lower levels than aloft. The conclusion of Matthews and Henz (1975), that accurate knowledge of boundary layer moisture and temperature discontinuities is needed for verification of cumulus models, is true for this study.

For nonfrontal convection of both prevailing and highest cloud top categories, the model produced reasonable estimates of the

convection temperature and top elevation without the necessity of intervention by a forecaster. But, for frontal cases when forecasting cloud tops, there is greater necessity to modify the input sounding than for nonfrontal cases. Forecasts obtained by using the unmodified sounding for the nonfrontal cases that had the lowest RMSE were not significantly different, at the 1% confidence level, from the lowest RMSE of the modified soundings. However, for frontal cases, the lowest RMSE of the modified soundings was significantly better, at the 1% confidence level, than the lowest RMSE of the unmodified sounding. Thus, a preliminary conclusion is that forecasters could concentrate on the more complex atmospheric structures.

The results from this modest-sized sample suggest that a simple cloud model run on a minicomputer does have the potential for providing the weather forecaster with an objective method of forecasting convection occurrence and convective cloud top heights.

5.1 Suggestions for future research

A simple one-dimensional cloud model has been shown to possess skill in forecasting convective cloud tops in an operational situation. However, several improvements may be possible.

Any cloud model used in cloud top prediction should have a variable surface pressure that can be specified by the forecaster. This option could allow the model to be used more accurately in various surface elevations. Also, this will allow the forecaster to specify the model's surface pressure to be at values different from the actual surface pressure to simulate convection that is decoupled from the surface. For example, in cases such as overrunning

and nocturnal convection, it is more reasonable to consider the warm moist air originating at the top of the surface-based inversion as being the base of convection than to consider the surface as the base.

Model height predictions are very dependent upon conditions in the boundary layer. In some cases, it might be a benefit to allow the forecaster the option of increasing the vertical resolution of the sounding interaction levels to every 2.5 kPa in the lower 10-20 kPa of the sounding.

With the model changes, experiments on nocturnal, cold season, and other types of convection that were not considered in this thesis could become easier to run. It would be useful to know whether the cloud model can yield height forecasts for convection at any time of the day or can best show the maximum afternoon convection. The case studies in this thesis were primarily keyed to late afternoon warm season verifications when the maximum cloud tops are usually observed.

It is hoped that the results presented in Chapter 4 will direct future workers to focus on the modifications and conditions that appear to be most promising. For example, future work on prevailing tops should be concentrated on a cloud radius near 2 km to see if there is a radius that significantly reduces the forecast error with respect to the 2 km radius results. Also, with a larger sample space, it may be possible to specify a bias for a set of given conditions that will result in reduced prediction errors.

Future research should be directed to see if the subjective sounding modifications made in this thesis are similar to the

modifications that other forecasters would make as was hypothesized. The development of objective sounding modification and surface dewpoint forecasting techniques would be desirable.

The cloud height forecast is only one of the many products of the cloud model. Future research should also be directed to see if there is a relationship between the implied and the observed precipitation amount, and between the calculated vertical velocities and the occurrence of severe weather events.

Implementation of some of the suggestions on how to improve the cloud model and its usage could result in better convection and cloud top forecasts than were obtained in this study. Possibly, improvements could lead to operational forecasting of convective cloud tops with the use of cloud models.

REFERENCES

Adler, R. F., and D. D. Fenn, 1978: Thunderstorm vertical velocities estimated from satellite data. Preprints Conf. Weather Forecasting and Analysis and Aviation Meteorology, Silver Springs, MD, Amer. Meteor. Soc., 206-210.

Anthes, R. A., 1977: A cumulus parameterization scheme utilizing a one-dimensional cloud model. Mon. Wea. Rev., 105, 270-286.

Austin, J. M., 1948: A note on cumulus growth in a nonsaturated environment. J. Meteor., 5, 103-107.

Barnum, D. C., D. E. Martin, A. T. Safford and J. L. Vogel, 1970: F. C. Bates' conceptual thoughts on severe thunderstorms. Bull. Amer. Meteor. Soc., 51, 481-488.

Bjerknes, J., 1938: Saturated adiabatic ascent of air through dry-adibatically descending environment. Quart. J. Roy. Meteor. Soc., 64, 325-330.

Bonner, W. D., and J. E. Kemper, 1971: Broad-scale relations between radar and severe weather reports. Preprints 7th Conf. Severe Local Storms, Kansas City, Amer. Meteor. Soc., 140-147.

Byers, H. R., and R. R. Braham, Jr., 1949: The Thunderstorm, U. S. Govt. Printing Office, Washington, D. C., 287 pp.

Cahir, J. J., J. M. Norman, W. D. Lottes and J. A. Toth, 1976: "New tools for forecasters: Real-time cross sections produced in the field. Bull. Amer. Meteor. Soc., 57, 1426-1433.

Cahir, J. J., J. M. Norman and D. A. Lowry, 1978: Use of a real-time computer graphics system for diagnosis and forecasting. Preprints Conf. Weather Forecasting and Analysis and Aviation Meteorology, Silver Springs, MD, Amer. Meteor. Soc., 194-196.

Darrah, R. P., 1978: On the relationship of severe weather to radar tops. Mon. Wea. Rev., 106, 1332-1339.

Fucik, N. F., and R. E. Turner, 1975: Data for NASA's AVE IV experiment: 25-MB sounding data and synoptic charts. NASA TM X-64952, NASA Marshall Space Flight Center, Alabama, 458 pp.

Hane, C. E., 1974: Observations needed to test numerical models of thunderstorms. Proceedings of Severe Environmental Storms and Mesoscale Experiment Project, Opening Meeting, Boulder, CO, 345-349.

Houghton, H. G., and H. E. Cramer, 1951: A theory of entrainment in convective currents. J. Meteor., 8, 95-102.

REFERENCES (Continued)

Klein, W. H., 1978: An introduction to the AFOS program. Preprints Conf. Weather Forecasting and Analysis and Aviation Meteorology, Silver Springs, MD, Amer. Meteor. Soc., 186-189.

Kreitzberg, C. W., and D. J. Perkey, 1976: Release of potential instability: Part I. A sequential plume model within a hydrostatic primitative equation model. J. Atmos. Sci., 33, 456-475.

Kuo, H. L., 1965: On formation and intensification of tropical cyclones through latent heat release by cumulus convection. J. Atmos. Sci., 31, 1232-1240.

Kuo, H. L., 1974: Further studies of the parameterization of the influence of cumulus convection on large-scale flow. J. Atmos. Sci., 31, 1232-1240.

Ludlam, F. H., and R. S. Scorer, 1953: Convection in the atmosphere. Quart. J. Roy. Meteor. Soc., 79, 317-341.

Mahrt, L., 1975: The influence of low level vertical gradients of moisture on parcel stability. Preprints Ninth Conf. Severe Local Storms, Norman, Okla., Amer. Meteor. Soc., 40-44.

Matthews, D. A., and J. F. Henz, 1975: Verification of numerical model simulations of cumulus-environmental interaction in the High Plains. Pure Appl. Geophys., 113, 803-823.

Myers, J. N., 1966: Application of slice theory to account for the horizontal extent of convective precipitation radar echoes. J. Appl. Meteor., 5, 832-838.

Panofsky, H. A., and G. W. Brier, 1968: Some applications of statistics to meteorology. The Pennsylvania State University, University Park, PA, 224 pp.

Petterssen, S., E. Knight, R. W. James and N. Herlofson, 1945: Convection in theory and practice. Geofys. Publ., 16, Nr. 10.

Sanders, F., and A. J. Garrett, 1975: Application of a convective plume model to prediction of thunderstorms. Mon. Wea. Rev., 103, 874-877.

Saunders, P. M., and F. C. Ronne, 1962: A comparison between the height of cumulus clouds and the height of radar echoes received from them. J. Appl. Meteor., 1, 296-302.

Schaefer, J., 1975: Moisture stratification in the "well-mixed" boundary layer. Preprints Ninth Conf. Severe Local Storms, Norman, Okla., Amer. Meteor. Soc., 45-50.

REFERENCES (Continued)

Simpson, J., G. W. Brier and R. H. Simpson, 1967: Stormfury cumulus seeding experiment 1965: Statistical analysis and main results. J. Atmos. Sci., 24, 508-521.

Simpson, J., and V. Wiggert, 1969: Models of precipitating cumulus towers. Mon. Wea. Rev., 97, 471-489.

Stommel, H., 1947: Entrainment of air into a cumulus cloud. J. Meteor., 4, 91-94.

Ulanski, S. L., and M. Garstang, 1978: The role of surface divergence and vorticity in the life cycle of convective rainfall. Part I. Observation and analysis. J. Atmos. Sci., 35, 1047-1062.

Vonnegut, B., R. M. Cunningham and R. E. Katz, 1946: Instruments for measuring atmospheric factors related to ice formation on airplanes. Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Weinstein, A. I., and L. G. Davis, 1967: A parameterized numerical model of cumulus convection. Rep. No. 11, Contract NSF GA-777, The Pennsylvania State University, 44 pp.

DATE
ILMED
-8